CP Parameters of the B^0_s at the Tevatron

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For the CDF and D0 collaborations

Montpellier QCD Workshop

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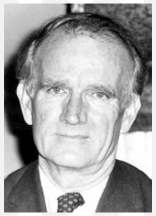
CP Violation

- Study of CP symmetry and its violation is a strong hint to the underlying of dynamics of particle interactions.



- A great example: Cronin & Fitch's discovery of CP violation in 1964 indicates (Kobayashi, Maskawa 1973) three generations of quarks.

- BSM CP violation in the B^0_s sector could indicate a fourth generation (see arXiv:0803.1234v3)

- Fascinating connection to cosmology, since the standard model has all of the ingredients to generate an $O(10^{-20})$ Baryon Asymmetry of the Universe $n_b/n_\gamma \sim 10^{-20}$, namely the three Sakharov conditions of baryon number violation, CP violation, and departure from thermal equilibrium. However n_b/n_γ measured to be $O(10^{-10})$.

CP violation in the B^0_s system

- The Tevatron produces all species of b-hadrons: B^0, B^+ but also B^0_s, B_c^+, Λ_b (Σ_b, Ξ_b, Ω_b…) excited states

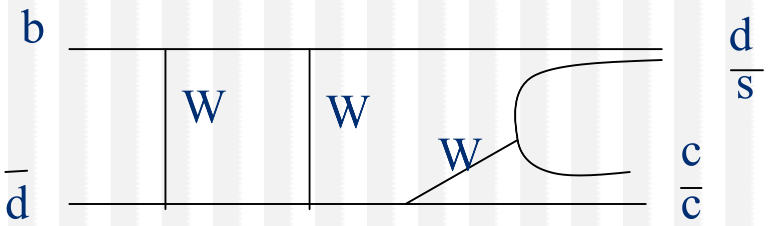
- In the B^0_s sector, two measurements stand out, because one can compare clean measurements to precise theory predictions:

- The measurement of the CP phase β_s in the decay of $B^0_s \rightarrow J/\psi\ \phi$
  - New measurement from CDF based on 5.2 fb^{-1}; older (2.8 fb^{-1}) measurements from D0

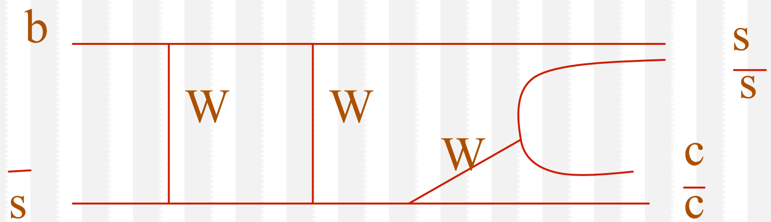
- The measurement of the semileptonic CP asymmetry A^b_{sl}
  - New measurement of the dilepton charge asymmetry from D0 (6.1 fb^{-1}); older (1.6 fb^{-1}) measurement from CDF.

- These both involve mostly the physics of the weak interaction.

The decay $B^0_s \to J/\psi\ \phi$ measures a CP phase similar to the angle β measured in $B^0 \to J/\psi\ K^0$ decay: we replacement a d antiquark by an s antiquark

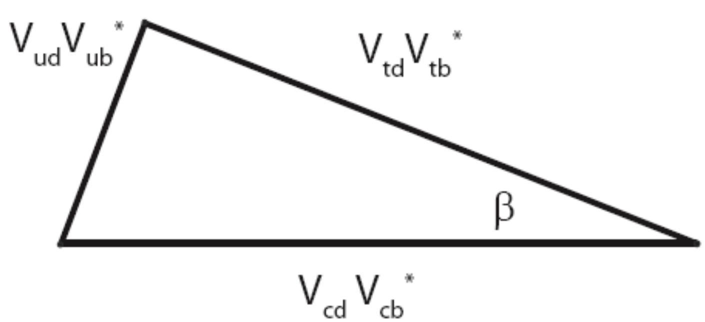


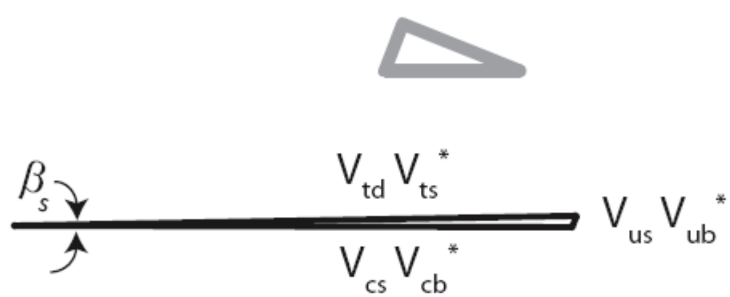
$B^0 \to J/\psi\ K^0$ $\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$



$B_s^0 \to J/\psi\ \phi$ $\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$

We are measuring not the (bd) unitarity triangle but the (bs) unitarity triangle:





$B^0_s \to J/\psi\ \phi$

- $B^0_s \to J/\psi\ \phi$ is two particles decaying to three final states..

Two particles:

$$\left|B^0{}_{S,L}\right\rangle = p\left|B_S{}^0\right\rangle + q\left|\bar{B}_S{}^0\right\rangle$$

$$\left|B^0{}_{S,H}\right\rangle = p\left|B_S{}^0\right\rangle - q\left|\bar{B}_S{}^0\right\rangle$$

Light, CP-even, shortlived in SM

Heavy, CP-odd, longlived in SM

Three final states:

$J/\psi\ \phi$ in an S wave	CP Even
$J/\psi\ \phi$ in a D wave	CP Even
$J/\psi\ \phi$ in a P wave	CP Odd

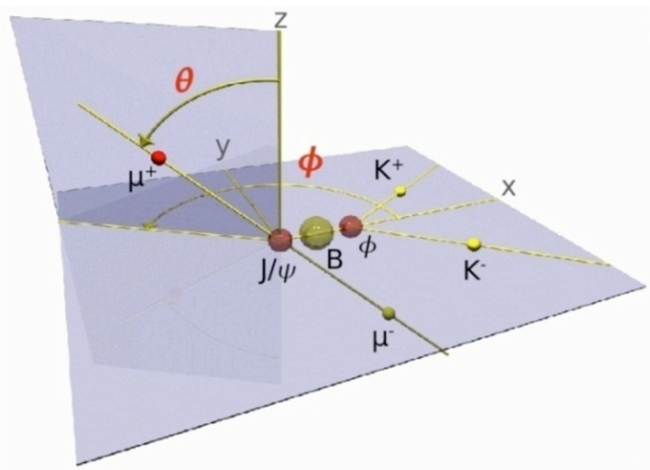
A supposedly CP even initial state decays to a supposedly CP odd final state…. like the neutral kaons

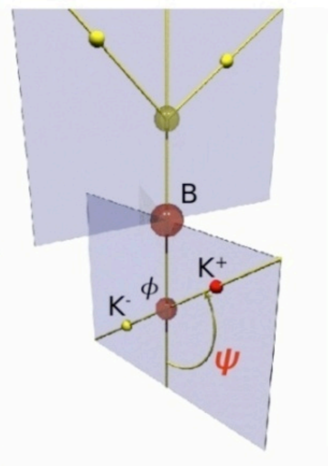
Measurement needs $\Delta\Gamma \neq 0$ but not flavor tagging.

The polarization of the two vector mesons in the decay evolves with a frequency of Δm_s

Measurement needs flavor tagging, resolution, and knowledge of Δm_s

The measurement is a flavor-tagged analysis of time-dependent angular distributions:





$$\hat{n} = (\sin\theta\cos\varphi, \sin\theta\sin\phi, \cos\theta)$$

$$\vec{A}(t,\psi) = \left(A_0(t)\cos\psi, \frac{-A_{\parallel}(t)\sin\psi}{\sqrt{2}}, i\frac{A_{\perp}(t)}{\sqrt{2}}\right)$$

$$P(\theta,\phi,\psi,t) = \frac{9}{16\pi}\left|\vec{A}(t,\psi)\times\hat{n}\right|^2$$

An analysis of an oscillating polarization.

We measure:

The CP phase β_s

Width difference $\Delta\Gamma_s$ in B^0_s system (as predicted by HQET)

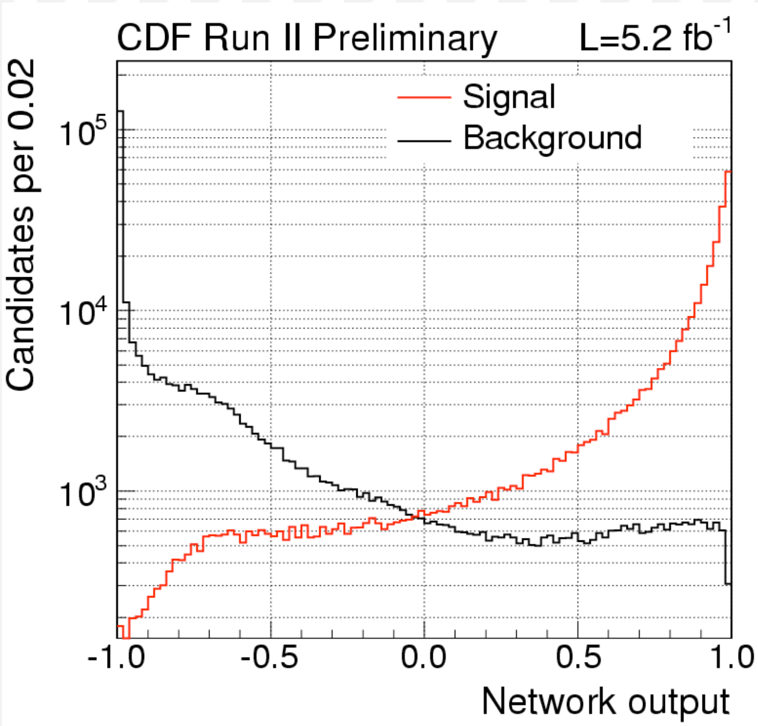
Lifetime of B^0_s (τ_s/τ_0 = 1.00 ±0.01 in HQET)

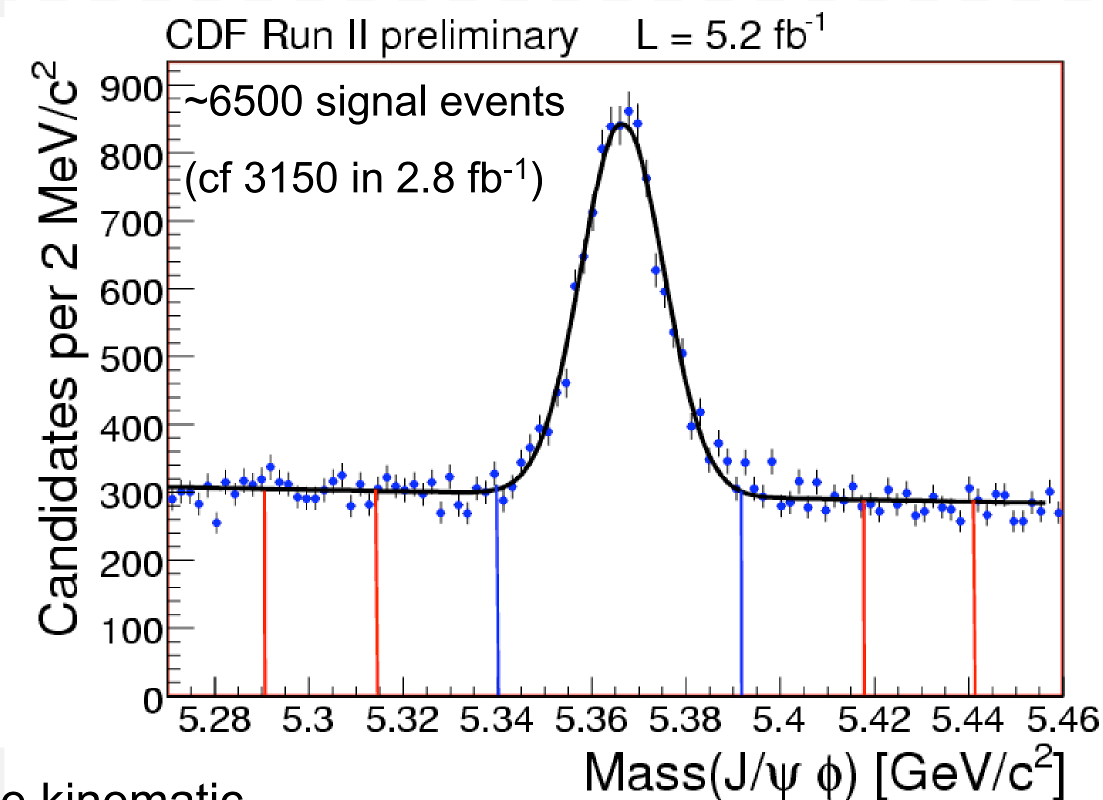
Polarization amplitudes and phases A_0, $A_\perp$,$A_{||}$, $\delta_\perp$,$\delta_{||}$

New: in this measurement we incorporate potential contamination from $B^0_s \rightarrow J/\psi\ K^+K^-$ (K^+K^- in an S-wave) the impact on our results was pointed out by Stone and Zhang Phys. Rev. D 79, 074024 (2009)

Data sample.

Event selection by neural network; the cut is optimized by choosing the best statistical error on β_s.

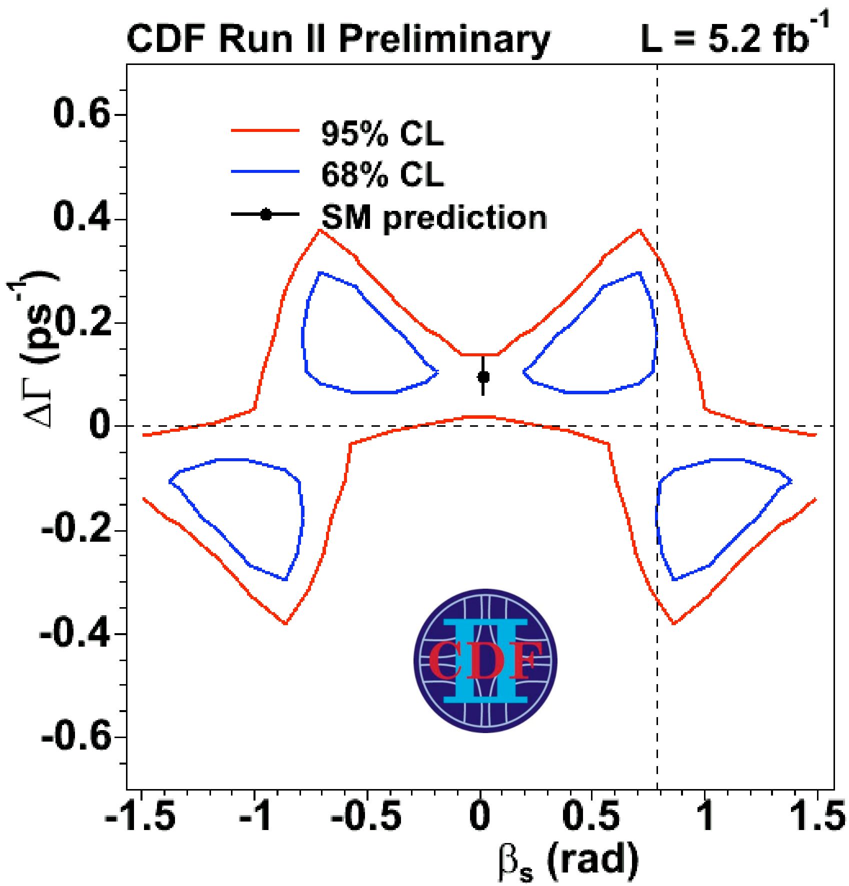




•Neural network inputs include kinematic variables as well as particle ID (TOF and dEdx).

*Optimized to minimize the error on β_s.

Constraints on β_s and $\Delta\Gamma_s$ without flavor tagging



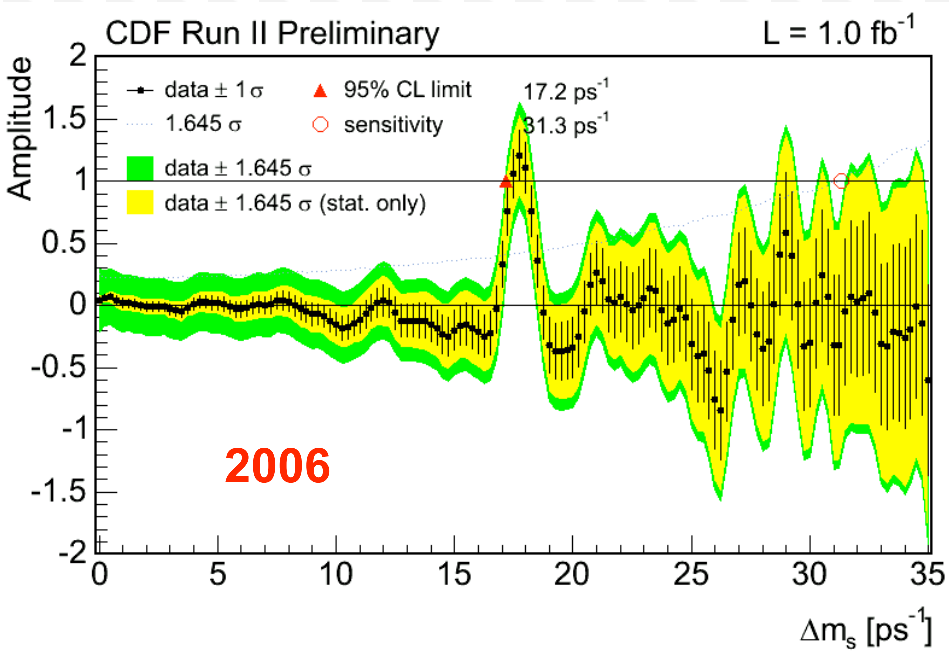
Next, we add flavor tagging, the determination of whether the strange bottom meson was born as a B^0_s or a $\bar{B}^0_s$.

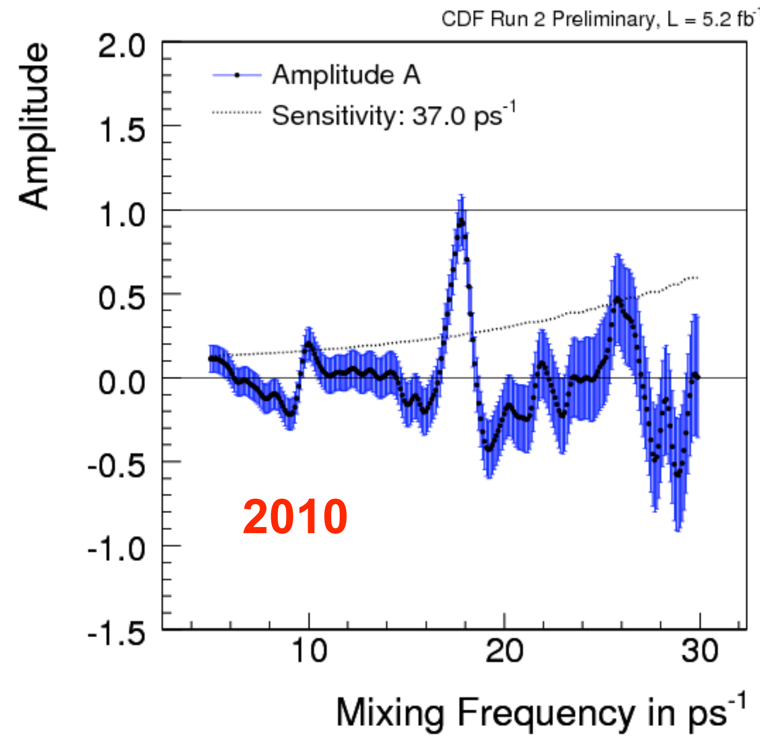
Two varieties of flavor tagging Are applied:

OST: "Opposite side tagging"
εD^2 ~ 1.8% *calibrated using fully reconstructed $B^{\pm}$ decays.*

SSKT: "Same side kaon tagging"
εD^2 ~ 3.2% *calibrated using B^0_s hadronic decays*

Same-side Kaon tagging calibrated for the first time since 2006 using B^0_s oscillations





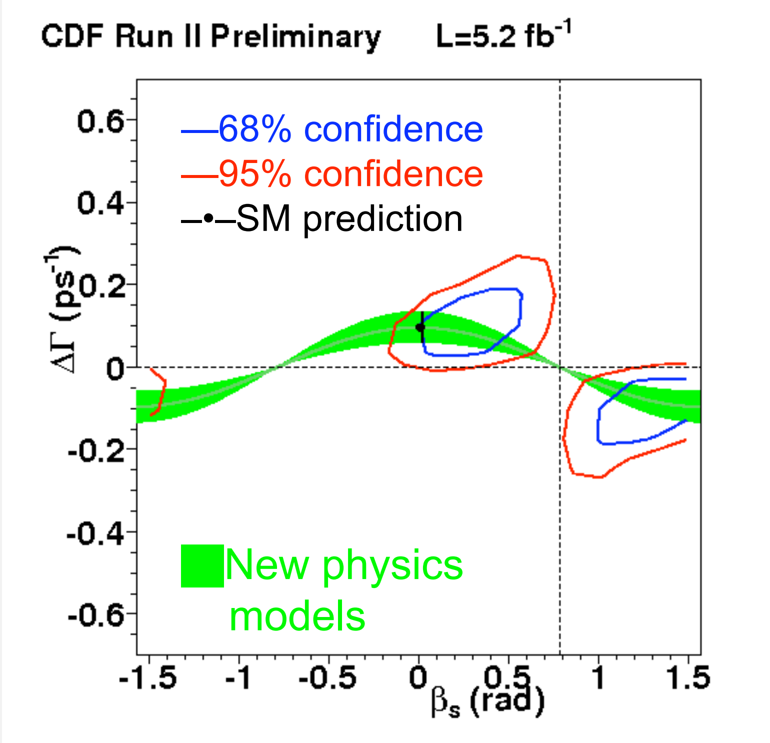
A = 0.94 ± 0.15 (stat.) ± 0.13 (syst.)
T = $\varepsilon A^2 D^2$ = (3.2 ± 1.4 (stat.+syst.)) %.

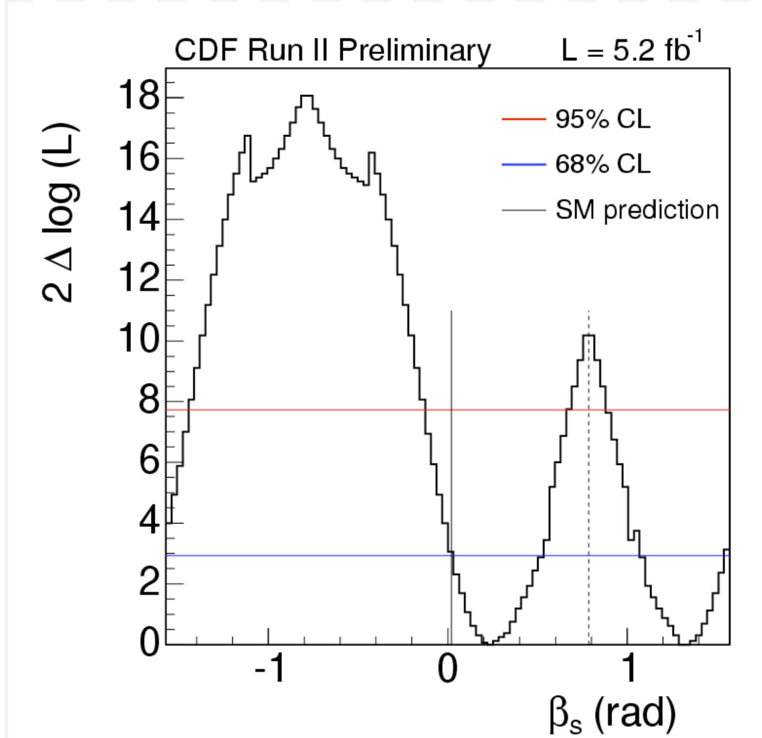
The measured physical quantities are in agreement with previous measurements:

$c\tau$ = 451.2 ± 5.5 (stat.) μm
Δm_s = 17.79 ± 0.07 (stat.)

$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to K^* K^-,\ K^* \to K^+ \pi^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to (3\pi)^-$$
$$B_s^0 \to D_s^- (3\pi)^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$

Results:

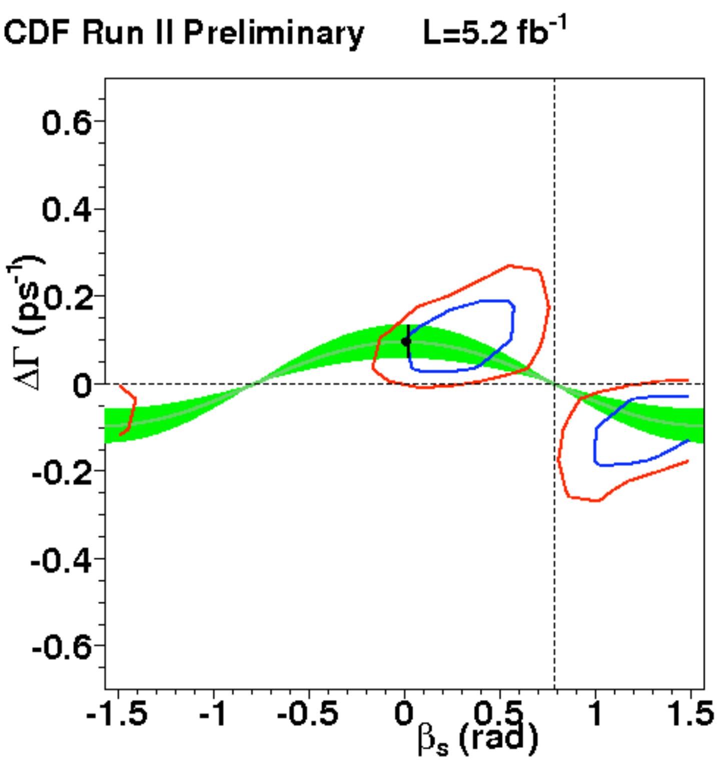


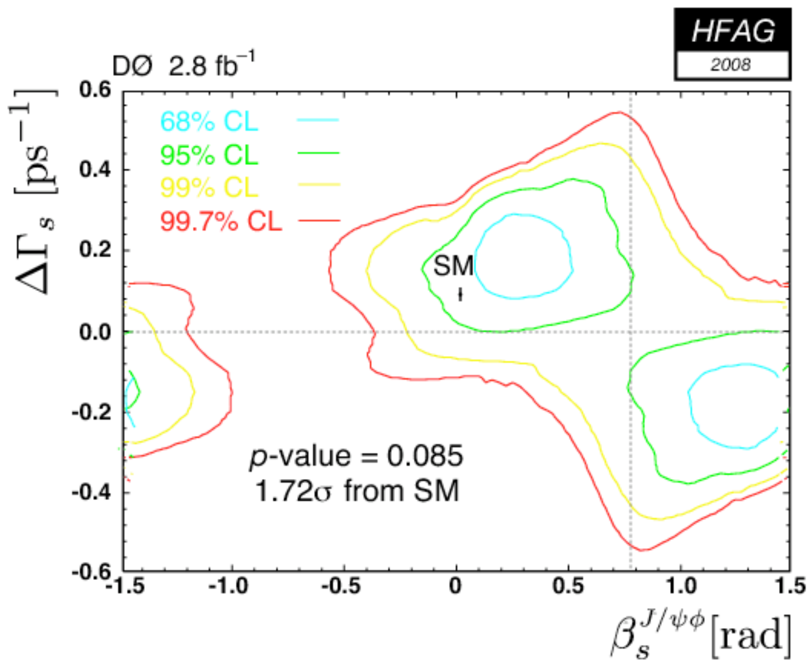


Comparing the green region with the contour tests the computation of Γ_{12} under the hypothesis of mixing induced CP violation independent of the value of β_s

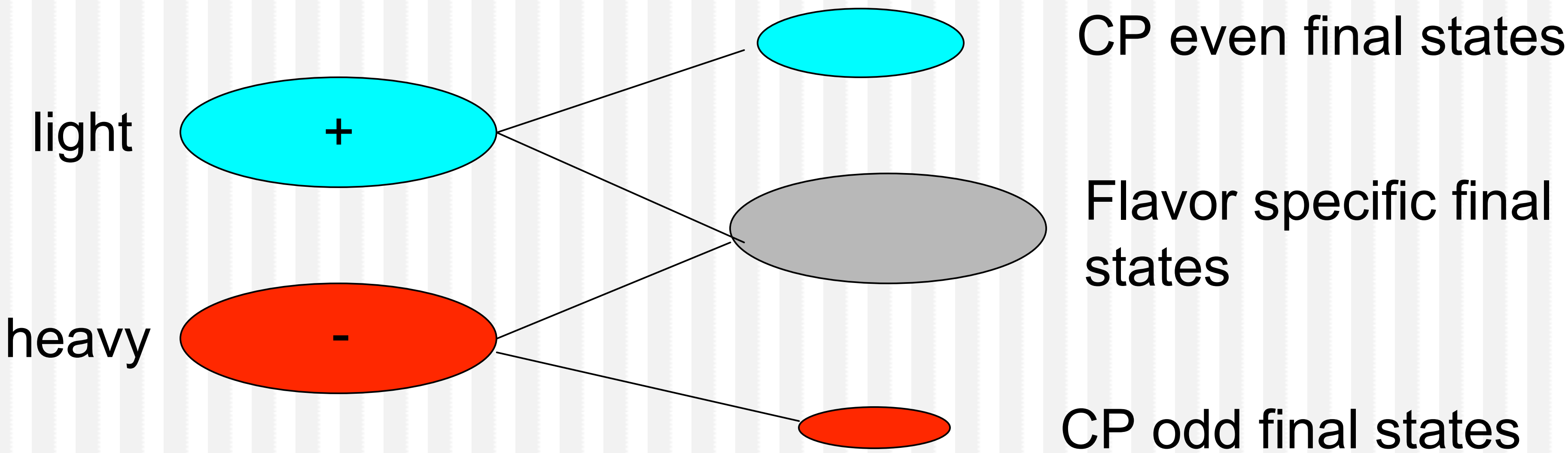
Comparing the confidence intervals in β_s with the Standard Model value value of β_s=0.019 tests for new sources of CP violation: we are ~1σ from the standard model=> no sign of new physics yet.

D0 are also in the game, but no update since 2.8 fb^{-1}

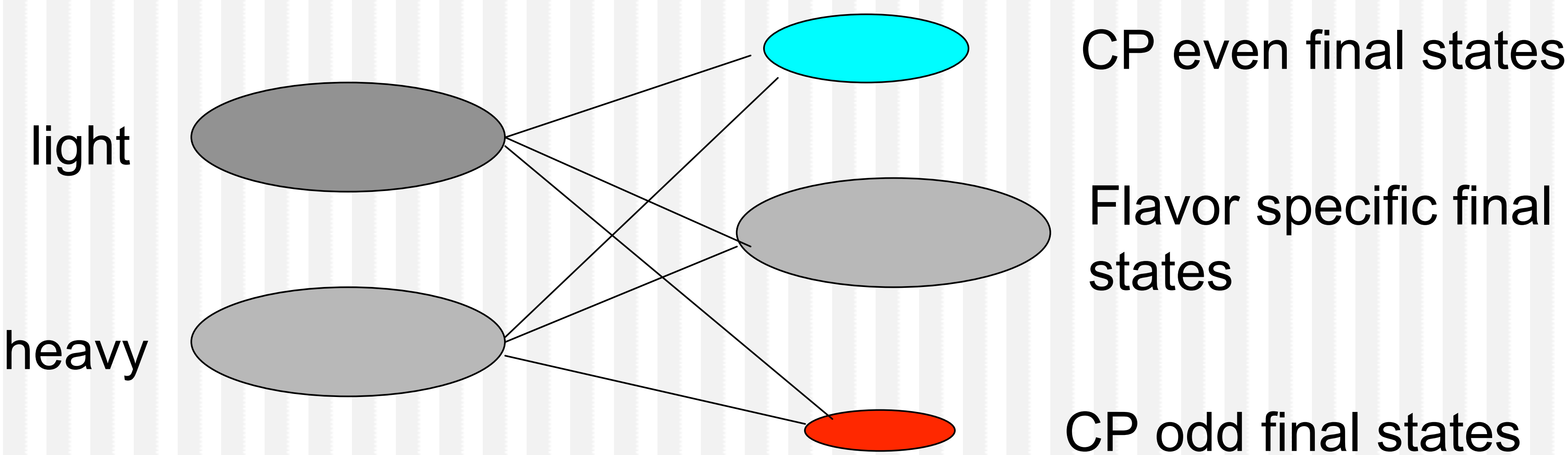




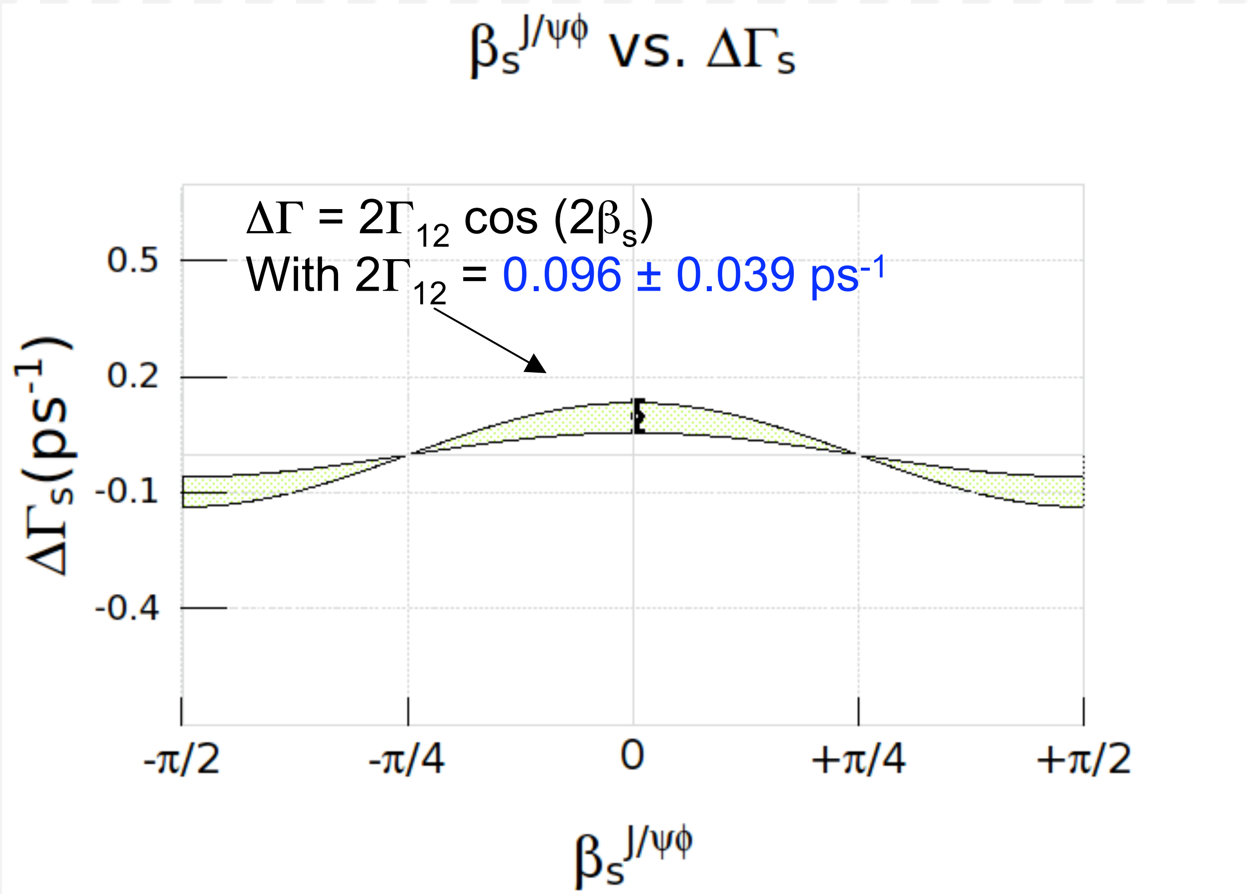
$\Delta\Gamma$ and β_s



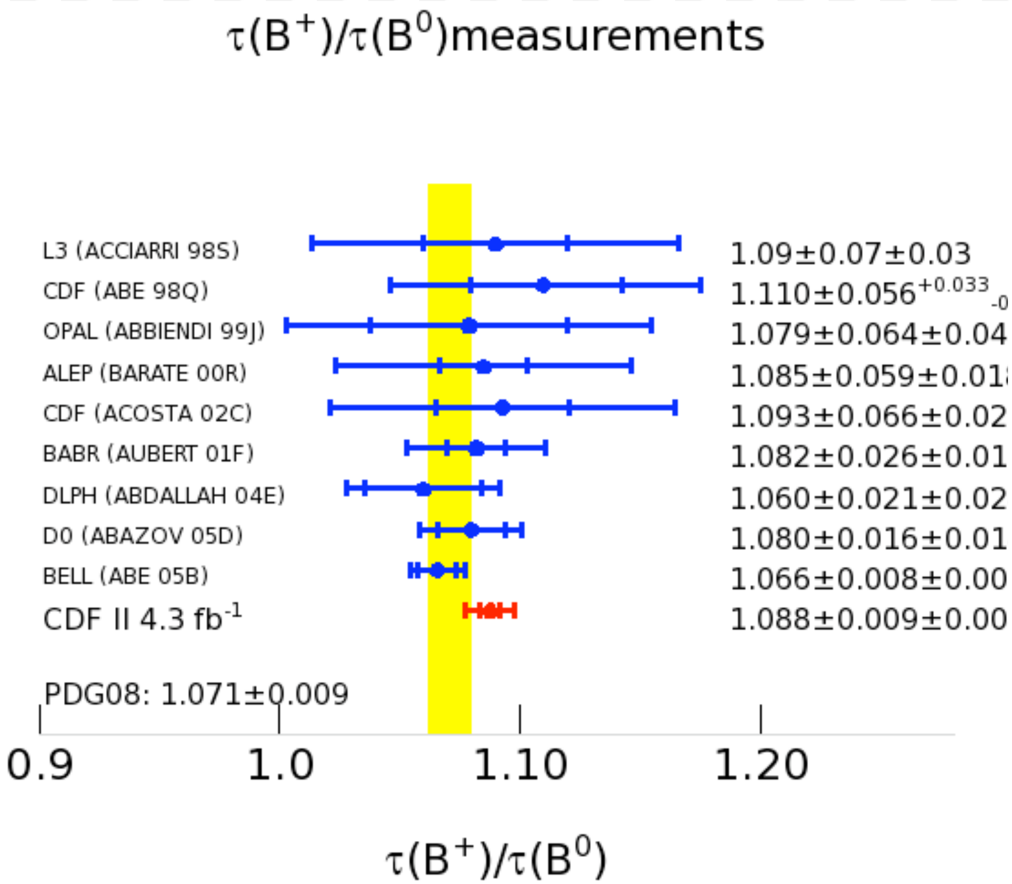
As we turn up Mixing-Induced CP violation ($\phi_{s,}$ $-2\beta_s$ in the SM) , the two mass eigenstates become equally mixed CP odd and even states:



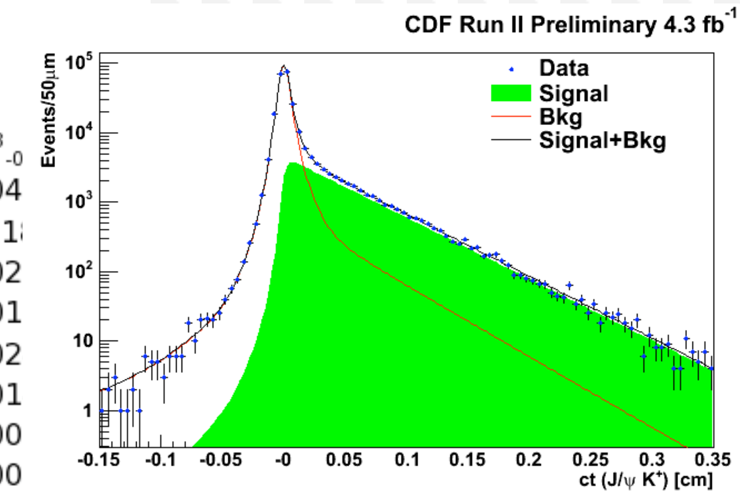
Mixing induced CP violation with Γ_{12} from HQE implies contraint on $\Delta\Gamma$ & β_s



Γ^s_{12} is an important quantity, it predicts band of values for $\Delta\Gamma$, β_s. The HQE used can be checked in lifetime ratios:



Theory prediction 1.063 ± 0.027 for this ratio.
Alexander Lenz arXiv:0802.0977

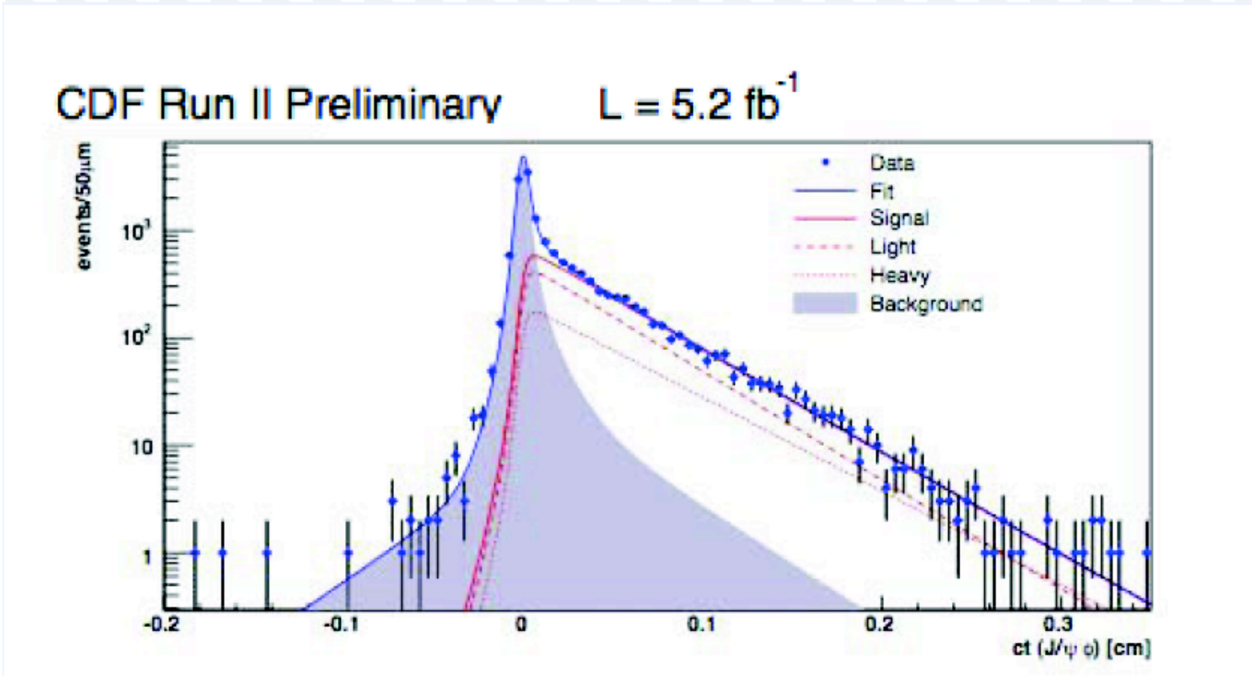


PDG world average and new CDF measurements in $B^+ \to J/\psi\ K^+$, $B^+ \to J/\psi\ K^0$

http://www-cdf.fnal.gov/physics/new/bottom/091217.blessed-JpsiX4.3/jpsix.html

in good agreement with HQE

The B^0_s lifetime τ_s is another check of the HQE. The $B^0_s \rightarrow J/\psi\ \phi$ analysis also contains the world's best measurement of τ_s, predicted to be equal to the B^0 lifetime τ_0 to within 1%.



$c\tau_s$ = 458.7 ± 7.5 (stat) ± 3.6 (syst) μm

$\Delta\Gamma_s$ = 0.075 ± 0.035 (stat) ± 0.01 (syst) ps^{-1}

compare $c\tau_0$ = (459±2.7 μm, PDG2008)

compare theory $\Delta\Gamma_s$=0.096 ± 0.039 ps^{-1}

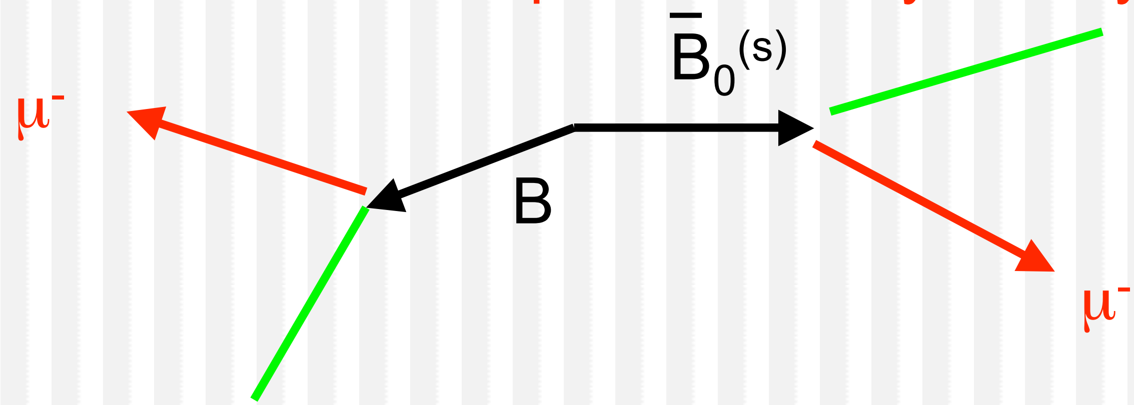
Lenz & Nierste JHEP0706:072,2007

$|A_{||}(0)|2$ = 0.231 ± 0.014 (stat) ± 0.015 (syst)

$|A_0(0)|2$ = 0.524 ± 0.013 (stat) ± 0.015 (syst).

$\varphi_\perp$ = 2.95 ± 0.64 (stat) ± 0.07 (syst)

Measurement of the semileptonic CP Asymmetry A^b_{sl} in D0



arXiv:1005.2757

Same sign muon pairs come from neutral B hadrons which oscillate into their antiparticles (e.g. B^0_s , 50% of the time).

An excess of negative muons will occur *if there is more b than $\bar{b}$ in the shortlived $B^0_{s,L}$, i.e. if $|q/p| > 1$*. This can happen at a low level, in the standard model.

$$a^q_{sl} = \frac{\Gamma(\bar{B}^0_q(t) \to \mu^+ X) - \Gamma(B^0_q(t) \to \mu^- X)}{\Gamma(\bar{B}^0_q(t) \to \mu^+ X) + \Gamma(B^0_q(t) \to \mu^- X)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

Both B^0 and B^0_s contribute, at the Tevatron; experimentally one measures

$A^b_{sl} = (0.506 \pm 0.043)\, a^d_{sl} + (0.494 \pm 0.043)\, a^s_{sl}$
$= (-2.3\ ^{+0.5}_{-0.6}) \times 10^{-4}$ using inputs from Lenz & Nierste hep-ph/0612167

You will notice that this mechanism depends on the existence of a decay width difference:

$$a_{sl}^q = \frac{\Gamma_q^{12}}{M_q^{12}} \cdot \sin\phi_q = (49.7 \pm 9.4) \times 10^{-4} \sin\phi_q$$

(hep-ph/0612167)

$$\phi_s \approx -2\beta_s$$

Like-sign dimuon charge asymmetry

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

N^{++}(N^{--}): number positive (negative) dimuon events. (Definition includes b-hadrons and backgrounds)

Inclusive muon charge asymmetry

$$a = \frac{n^+ - n^-}{n^+ + n^-}$$

n^+(n^-): number positive (negative) inclusive muons (Definition includes b-hadrons and backgrounds)

These two quantities are measured, then related to A^b_{sl}

1.495×10^9 inclusive muons

$a = (0.955 \pm 0.003)\%$

$$a = k\,A^b_{sl} + a_{bkg}$$
$$A = KA^b_{sl} + A_{bkg}$$

K and k are not unity
Because of decays like $b \to c \to \mu^+$
Their value is taken from simulation.

3.371×10^6 dimuons

$A = (0.564 \pm 0.053)\%$

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1-f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2-F_{bkg})\Delta$$

Kaon asymmetries a_k, A_k from data ($K^{*0} \to K^+\pi^-$ and $\phi \to K^+K)^-$)
Pion and proton asymmetries a_π, A_π, a_p, A_p from data ($K^0_s \to \pi^+\pi^-$ and $\Lambda^0 \to p\pi^-$)
.. *where charged tracks satisfy muon selection cuts.*

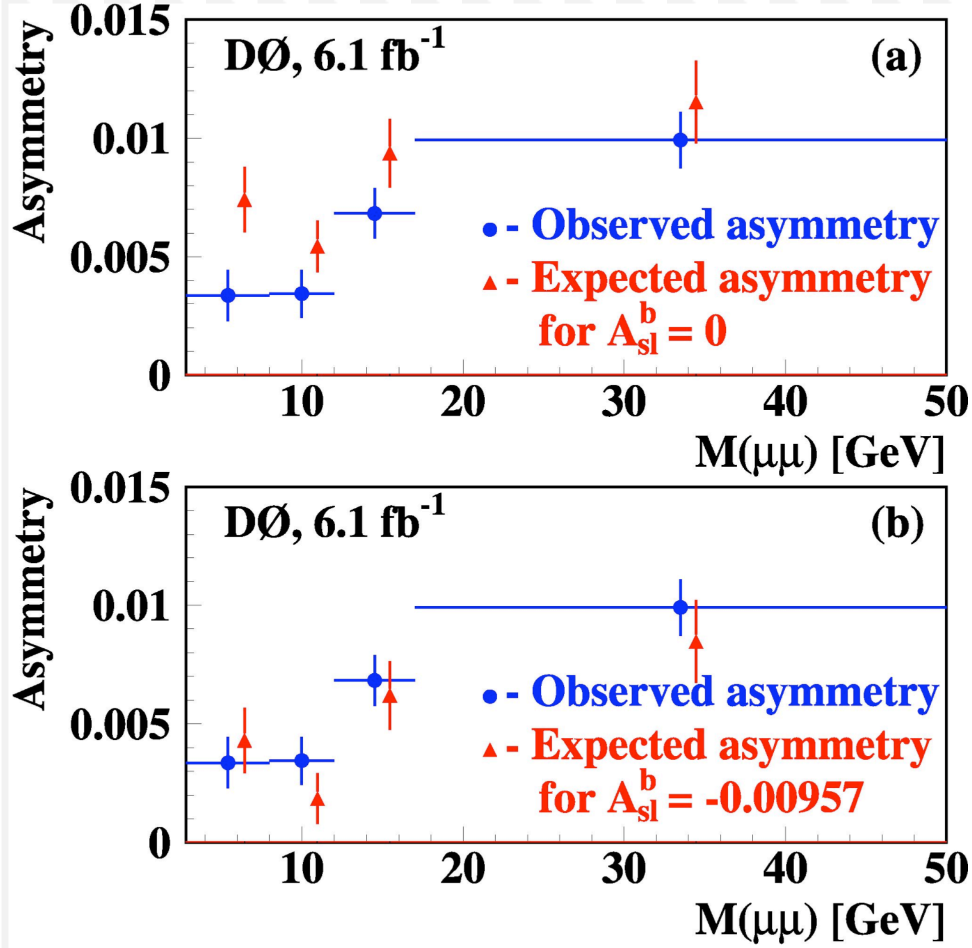
Kaon fractions f_k, F_k from analysis of $K^{*0} \to K^+\pi^-$ and $K^{*+} \to K^0_s\pi^+$.
Pion and proton fractions f_π, F_π, f_p, F_p from f_k, F_k with additional input from Monte Carlo on n_π/n_K and n_p/n_K

Muon reconstruction asymmetries δ and Δ from $J/\psi \to \mu+\mu-$ events.

Dimuon charge asymmetry

$A^b_{sl} = (-0.957 \pm 0.251(stat) \pm 0.146(syst))\%$

$A^b_{sl}(SM) = (-0.023\,^{+0.005}_{-0.006})\%$



Discrepancy at the 3.2 σ level.

Compare CDF, 1.6 fb^{-1}:
$A^b_{sl} = (0.80 \pm 0.90(stat) \pm 0.68(syst))\%$

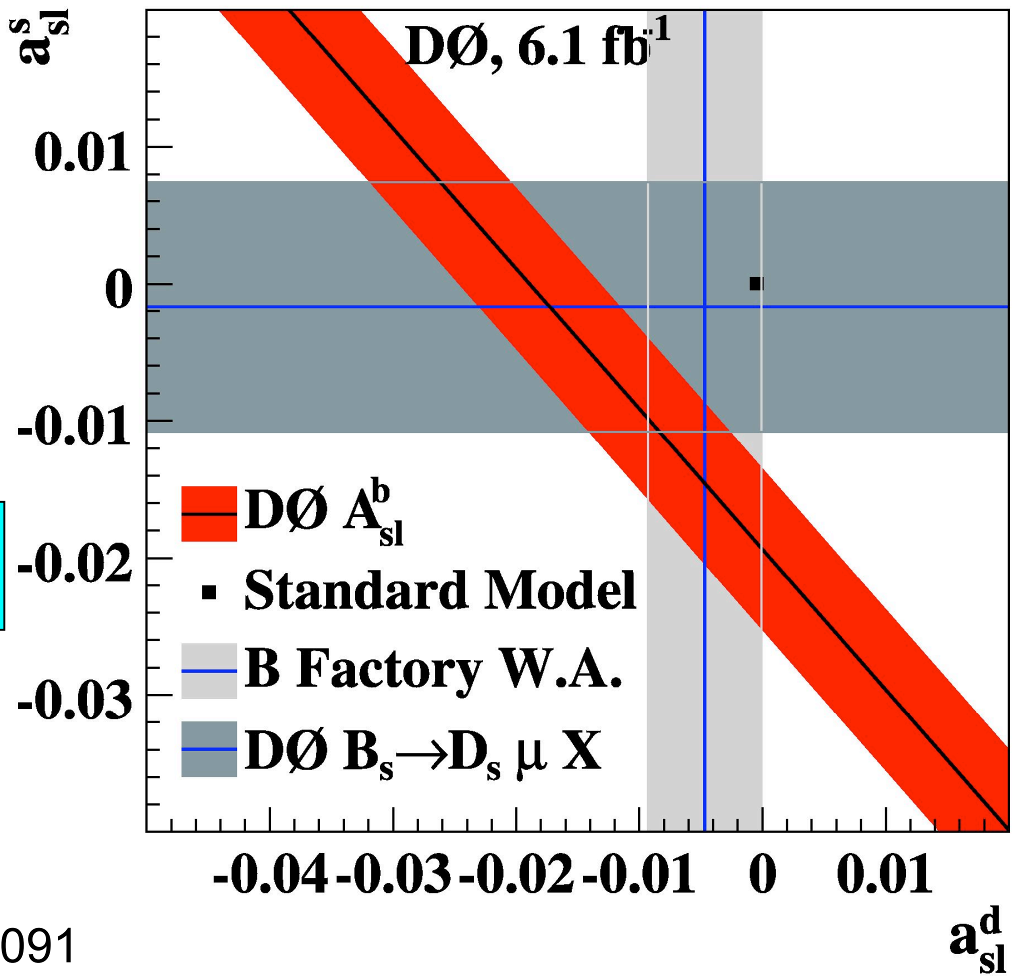
D0 then goes on to
Interpret the discrepancy
As an anomalous value of
a^s_{sl} from an anomalously high value of ϕ_s as we shall see ☛

Extract a^s_{sl}

a^s_{sl} is then extracted using additional input from the b-factories on a^d_{sl}, and Tevatron measurements of fragmentation fractions:

a^s_{sl} = (-1.46±0.75)%

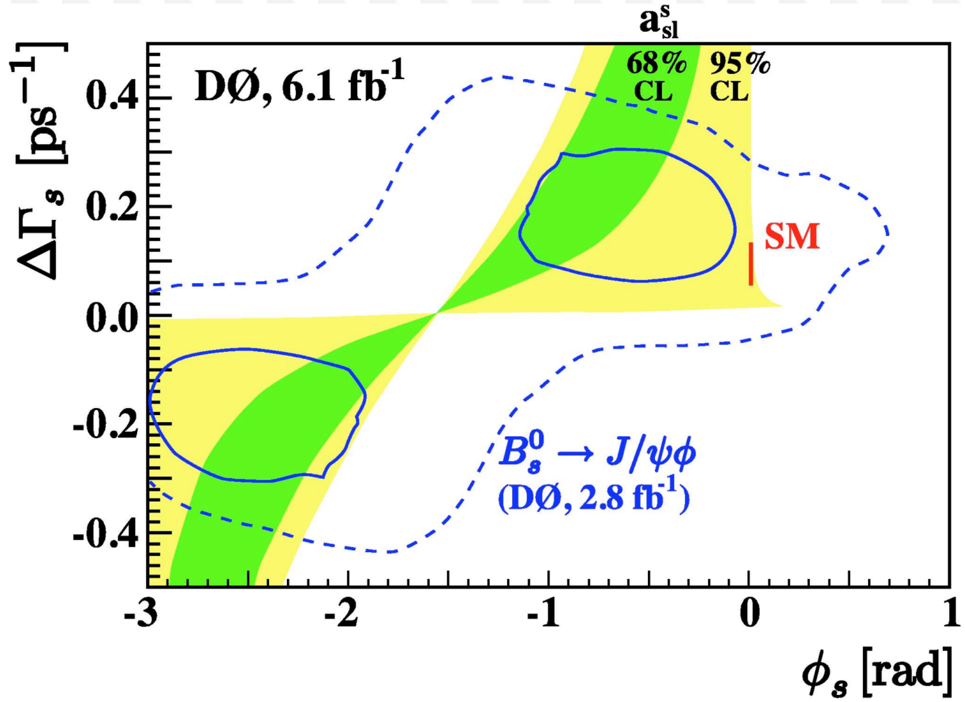
a^s_{sl}(SM)= (+0.0021±0.0006)%



Result consistent with Independent D0 measurement Using partially reconstructed B^0_s decays: a^s_{sl} = -0.0017±0.0091 arXiv:0904.3907

Extract bounds on ϕ_s ,$\Delta\Gamma$

Bounds on ϕ_s and $\Delta\Gamma$ are extracted with the assumption of mixing-induced CP violation:



Take

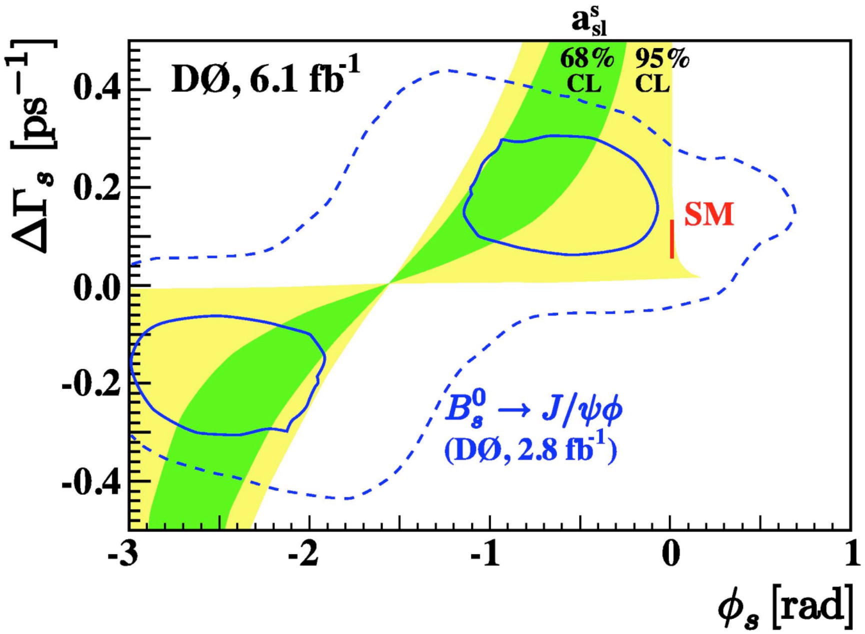
$$a_{sl}^{q} = \frac{\Gamma_q^{12}}{M_q^{12}} \cdot \sin\phi_q$$

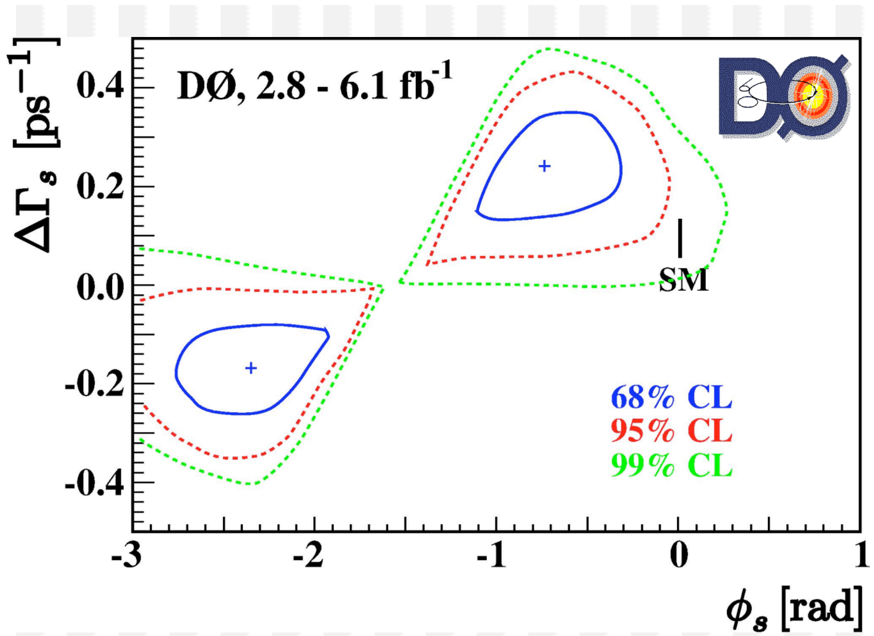
$$\Delta M_s = 2|M^{12}|$$

$$\boxed{\Delta\Gamma_s = 2|\Gamma^{12}| \cdot \cos\phi_s}$$

$$\longrightarrow \quad a_{sl}^{s} = \frac{\Delta\Gamma_q}{\Delta M_q} \cdot \tan\phi_s$$

(Reminder, this is the condition of Mixing induced CP violation!)



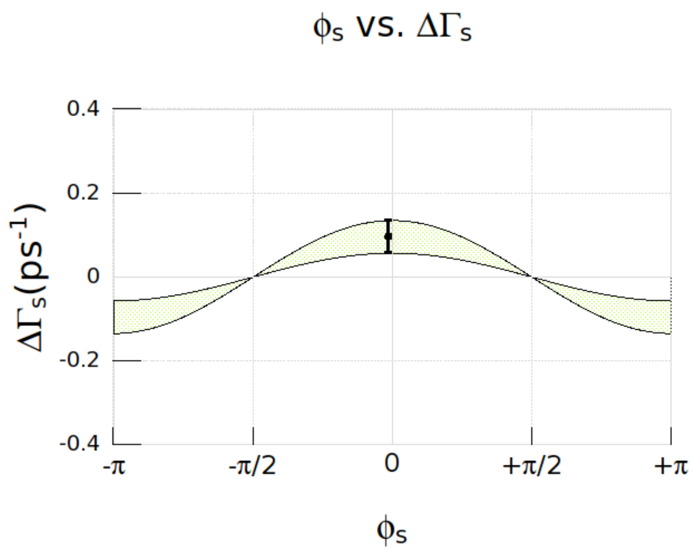


The D0 analysis of J/ψ φ and the D0 muon asymetries are consistent and can be combined in the context of Mixing Induced CP Violation.

But then one can compare this with theoretical predictions of Γ_{12}, which also imply bounds in the same parameter space, and there is some tension because:

$$a^q_{sl} = \frac{\Gamma^{12}_q}{M^{12}_q} \cdot \sin\phi_q = (49.7 \pm 9.4) \times 10^{-4} \sin\phi_q$$

compare $a^s_{sl} = (-1.46 \pm 0.75)\%$



See Bauer & Dunn arXiV:1006.1629 for comments on new physics contributions to Γ_{12}

Conclusions

- CDF reports an updated measurement of the CP violating phase β_s, now more precise and consistent with the standard model at ~ 1σ level.
- D0 reports a 3.2 sigma anomaly in the semileptonic CP asymmetry A^b_{sl}.
- In the context of Mixing Induced CP violation:
  - The β_s measurements (CDF,D0) are consistent with hypothesis.
  - The D0 a^s_{sl} measurement is consistent with the β_s measurements
  - The a^s_{sl} measurements seems to center in an unphysical region, but maybe OK within errors for the highest values of β_s
  - A certain tension presently exists between the three sources of bounds on β_s and $\Delta\Gamma$.
  - LHCb inherits a situation that I personally find a little unclear.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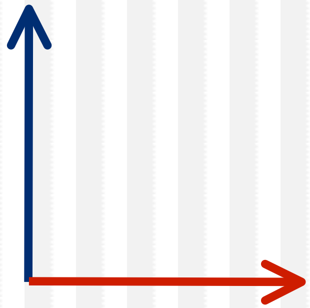
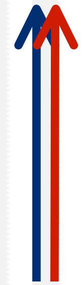
Time dependence of the angular distributions: use a basis of linear polarization states of the two vector mesons $\{S, P, D\} \rightarrow \{P_\perp, P_{||}, P_0\}$



CP odd states decay to $P_\perp$

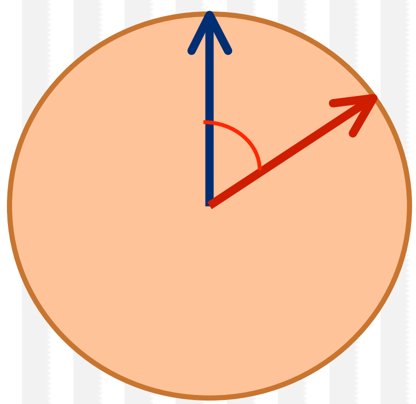


CP even states decay to $P_{||}$, P_0

If $[H,CP] \neq 0$

Then $\boxed{\frac{d}{dt}\langle CP \rangle \neq 0}$

$\Delta m_s \sim 17.77\ ps^{-1}$.



- The polarization correlation depends on decay time.
- Angular distribution of decay products of the J/ψ and the ϕ analyze the rapidly oscillating correlation.

A. S. Dighe, I. Dunietz, H. J. Lipkin, and J. L. Rosner, Phys. Lett. B 369, 144 (1996), 184 hep-ph/9511363.

reference material

$$\hat{n} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$$

$$\vec{A}(t) = (A_0(t)\cos\psi, -\frac{A_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{A_\perp(t)}{\sqrt{2}})$$

$$P(\theta,\varphi,\psi,t) = \frac{9}{16\pi}|\vec{A}(t)\times\hat{n}|^2$$

An analysis of the decay can be done with either a mix of B and $\overline{\mathrm{B}}$ mesons (untagged) or with a partially separated sample (flavor tagged). Latter is more difficult and more powerful.

$$A_i(t) = \frac{a_i e^{-imt} e^{-\Gamma t/2}}{\sqrt{\tau_H + \tau_L \pm \cos 2\beta_s} \cdot (\tau_L - \tau_H)} \left[E_+(t) \pm e^{2i\beta'} E_-(t)\right]$$

B

$$\overline{A}_i(t) = \frac{a_i e^{-imt} e^{-\Gamma t/2}}{\sqrt{\tau_H + \tau_L \pm \cos 2\beta_s} \cdot (\tau_L - \tau_H)} \left[\pm E_+(t) + e^{-2i\beta_s} E_-(t)\right] \cdot$$

$\overline{\mathrm{B}}$

$$E_\pm(t) = \frac{1}{2}\left[e^{+(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m}{2})t} \pm e^{-(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m}{2})t}\right]$$

These expressions are:

* used directly to generate simulated events.

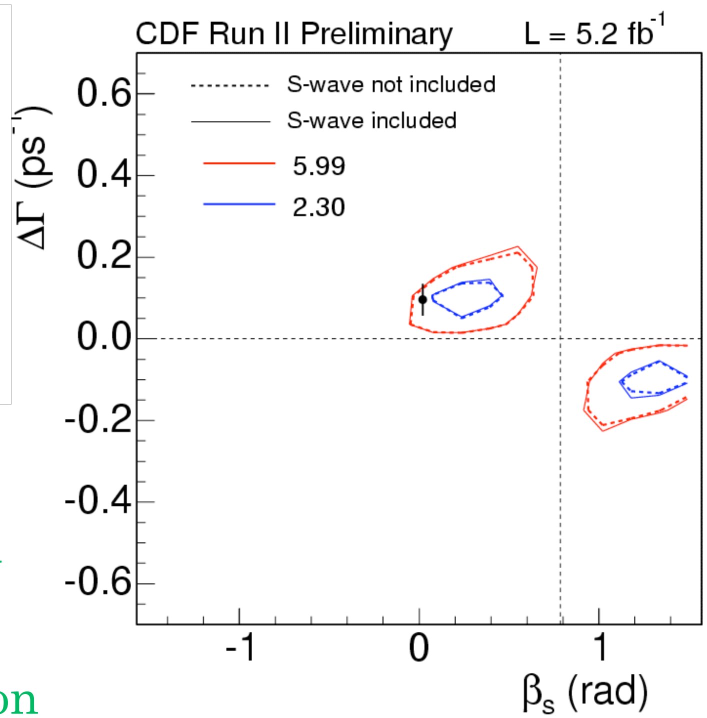
* expanded, smeared, and used in a Likelihood function.
* summed over B and $\overline{\mathrm{B}}$ (untagged analysis only)

Modifications to the Likelihood for the S-wave contamiation

You also need this for the S-wave component:

$$\vec{B}(t) = (B(t),0,0)$$

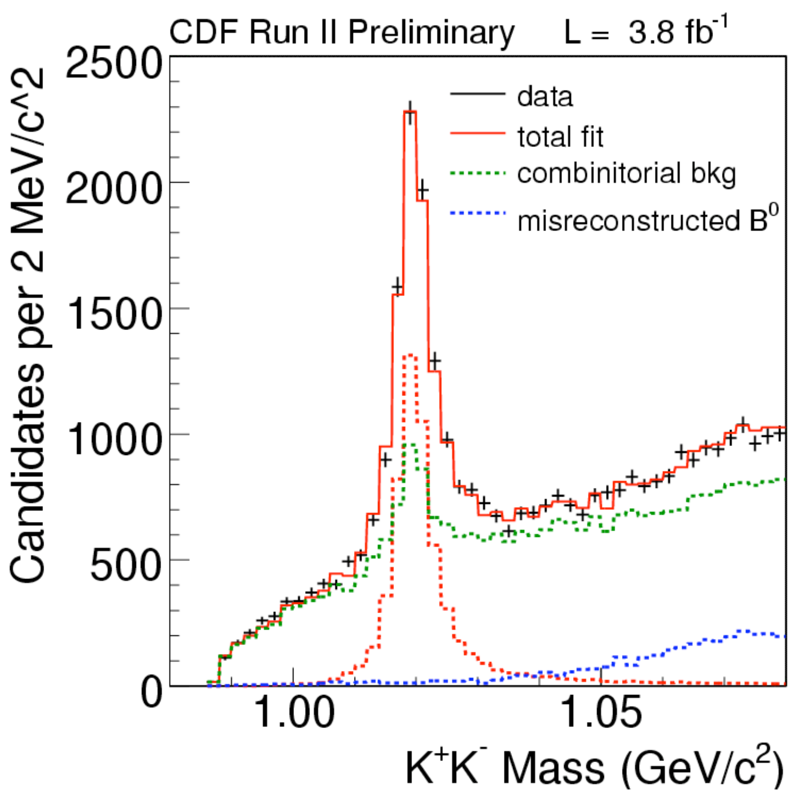
$$Q(\theta,\phi,\psi,t) = \frac{3}{16\pi} |\vec{B}(t) \times \hat{n}|^2$$

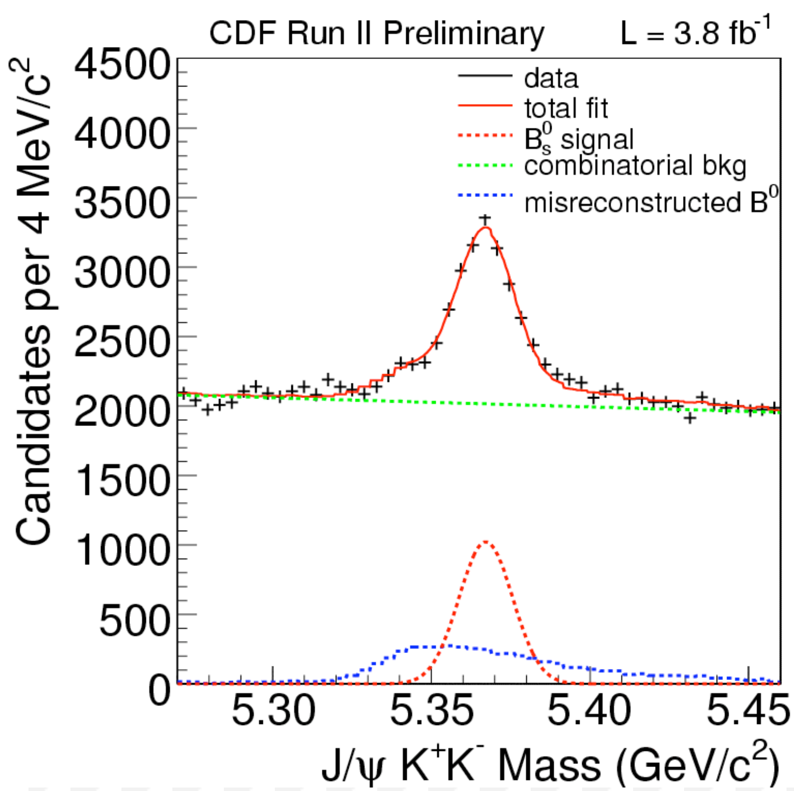


- S-wave is pure CP odd
- ϕ-mass dependence: nonrelativistic BW
- includes P-wave S-wave interference.
- and the proper detector re-normalization after the detector sculpting.

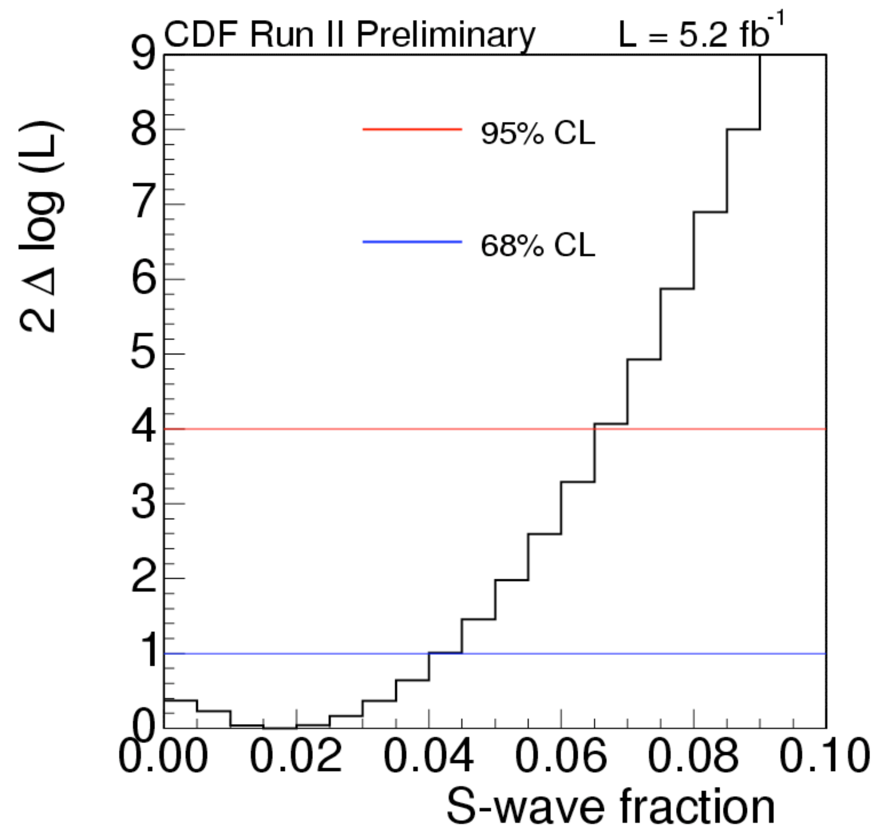
KK mass shape in the region of the ϕ

Invariant KK mass (left)
Combinatorial background from B^0_s sidebands.
B^0 reflections: shape from MC,
Fractions from B^0_s mass fit (right)





Fitted S-wave fraction:



Source	A^b_{sl} inclusive muon	A^b_{sl} dimuon	A^b_{sl} combined
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

Dominant uncertainties